The manuscript examines the spatio-temporal variability of marine heatwaves (MHWs) in the North Sea and explores how different large-scale climate variabilities interact to shape their occurrence and characteristics. The authors use long-term SST observations, identify two main regional patterns of MHW variability, and relate these patterns to different atmospheric and oceanic climate modes, with a primary focus on seasonal differences.

Overall, the topic is important and highly relevant, especially given the increasing frequency and impacts of marine heatwaves in shelf seas. The focus on the North Sea is well chosen, and the approach of examining the combined influence of climate modes, rather than treating them independently, is interesting. The study appears scientifically sound, and the results are clearly relevant to the community.

However, I believe the manuscript still requires major revisions. My main concern the lack of several methodological details and the presentation, particularly in the results section, which makes it difficult to follow the main results and understand them. With significant improvements in clarity and structure, the paper could be much stronger.

Response: Thank you very much. We carefully considered each of your comments and suggestions, and we would like to respond to them in the following content.

Introduction

1. The introduction provides useful background, but the aim of the study is not clearly stated. I strongly recommend rewriting the objectives part of the introduction to clearly state the goal(s) of the work and the main research questions.

Response: We thank the reviewer for this constructive suggestion. We agree that the original Introduction does not sufficiently highlight the specific aims of the study. We will rewrite the objectives part of the Introduction to clearly state the main goals of the work and the specific research questions regarding the regional variability of marine heatwaves and their links to large-scale climate modes.

2. Additionally, since the analysis relies heavily on different climate modes, it would be helpful to define these climate modes early on, either in the introduction or in the data/methodology section. And add a brief explanation of how the positive and negative phases of these modes could affect SST variability in the North Sea.

Response: We agree that a clear definition of the climate modes and their relevance to North Sea SST variability should be provided early in the manuscript. We will revise the manuscript to explicitly define all climate modes used in this study and to clarify their physical relevance. Specifically, a new subsection (Sect. 2.4) will be added to the Methods section, which details the definitions, data sources, and calculation methods of the NAO, EAP, and AMV indices. In addition, the Introduction will be revised to include a concise description of how the positive and negative phases of these climate modes can influence SST variability and marine heatwaves in the North Sea through atmospheric circulation, and oceanic processes.

3. One minor point: the manuscript sometimes refers to the Atlantic Multidecadal Oscillation as AMO and sometimes as AMV. Please use only one term throughout the manuscript, as switching between them is confusing.

Response: Thank you for pointing this out. We will revise the manuscript and consistently use AMV.

Data and Methods

This section requires the most attention, primarily because important details are missing or not clearly described.

1. The data section is not sufficiently clear. I suggest rewriting it in a more straightforward manner, listing the datasets used, their sources, temporal and spatial resolution, and how they are used in the analysis. Currently, it is difficult to understand exactly which products are used and why.

Response: We agree that the current Data section is not sufficiently clear and that the description of the datasets and their roles in the analysis can be confusing. In the revised manuscript, we will rewrite and reorganize the Data section in a more straightforward and structured manner. Specifically, we will clearly list all datasets used, including their sources, temporal and spatial resolutions, and describe how each dataset is used in the different parts of the analysis. This reorganization will also incorporate additional references and details for key datasets such as ERA5 and ORAS5, addressing related comments raised by you and Reviewer 1.

2. The SST analysis is limited to 2021, but high-resolution SST products are available at least until the end of 2024. It is unclear why the study stops at 2021. If this limitation is due to other variables or datasets, it should be clearly stated. Otherwise, extending the analysis to include the most recent years would strengthen the study, especially since recent years include strong extremes that could affect the statistics.

Response: Thank you for raising this important point regarding the temporal coverage of the SST analysis. The original manuscript uses the OSTIA reprocessed SST product, which is a long-term, homogeneous dataset specifically designed for climate studies and marine heatwave statistics. At the time when the data were processed and the manuscript was prepared, this reprocessed dataset was available only up to 2021, which explains the end year of the original analysis.

We note that near-real-time OSTIA SST products, which extend to present day, are available. However, these products are not reprocessed and may involve changes in input data streams and processing procedures over time, making them less suitable for consistent long-term climatological and MHW analyses. For this reason, we did not combine the NRT product with the reprocessed dataset.

We realized that the reprocessed OSTIA SST dataset has been updated and now extends through 2023. In the revised manuscript, we will extend the SST analysis to include the newly available

years (2022-2023), assess their influence on the MHW statistics, and update the temporal coverage and rationale for dataset selection in the Data section.

3. Regarding the marine heatwave definition, the authors use the standard Hobday et al. method, but the climatology period used to define the MHW threshold is not mentioned. It must be included in the methodology. Also, please clarify whether the same climatology baseline period is used when computing other anomalies in the study, as this is not currently clear.

Response: The marine heatwaves are identified using the standard Hobday et al. methodology, with the climatological mean and threshold computed over the 1982-2021 period, consistent with the temporal coverage of the SST dataset. In addition, all other anomalies analyzed in this study are calculated relative to the same 1982-2021 climatological baseline. We will clarify these points in the Methods section.

4. Another confusing aspect is the detrending or trend removal. In lines 109–110, the manuscript refers to trended and detrended data, but it is not clearly explained: how the detrending is performed? and how it affects the results? This needs a clearer explanation, as detrending choices can influence both clustering and correlations with climate modes.

Response: The detrending procedure will be clarified in the revised manuscript. Specifically, long-term warming is removed by estimating a linear trend of the global-mean SST over the study period (1982-2021). Monthly global-mean SST is then calculated and linearly interpolated to daily resolution, after which a linear regression is applied to obtain the global SST trend. This global trend is then subtracted from the original SST field prior to marine heatwave detection.

This approach follows common practice in MHW studies and is intended to remove the externally forced warming signal while retaining internal variability. As a result, the clustering and the relationships with climate modes reflect variability relative to the evolving background state, rather than being dominated by the long-term warming trend. We will add a description of this procedure and its rationale in the Methods section.

5. I also recommend a minor change in the subsection title in the methods (line 106). The subtitle is "Cumulative Intensity of Marine Heatwaves," but the section actually describes the overall MHW calculation and detection method and includes multiple metrics. A title such as "Marine Heatwave Calculation" would be more accurate and clearer.

Response: We agree that the original subsection title was too specific. The subsection title will be updated to more accurately reflect the content of the section.

6. I was confused by the calculation of the "cumulative intensity anomaly." Since MHWs are already defined as anomalous events, it is not clear why an additional anomaly is needed. If the authors choose to keep this variable, they need to clearly explain its importance and what additional information it provides.

Response: Thank you for raising this point. The MHWCI anomaly is introduced for a different purpose. In this study, the cumulative intensity is used to quantify the total impact of all MHW events occurring within a given year or season. The anomaly of this metric is then calculated to emphasize interannual variability, allowing a direct comparison of how active or inactive different years are relative to the long-term mean. We acknowledge that this distinction was not sufficiently clear in the current manuscript. In the revised version, we will clarify the rationale for using cumulative intensity anomalies and explain the additional information they provide beyond the event-based MHW definition.

7. Since the analysis relies heavily on seasons, the seasonal divisions should be clearly stated and justified. Currently, there is no clear explanation of why these particular seasonal divisions are chosen or what they represent physically for the North Sea.

Response: Thank you for this comment. We acknowledge that, although the seasonal divisions (DJF, MAM, JJA, SON) are explicitly defined in the Methods section, their physical relevance to the North Sea was not sufficiently explained.

These seasonal divisions correspond to well-established physical regimes in the North Sea, including weakening of the winter thermal stratification and summer stratification with shallow mixed layers. Similar seasonal definitions have been widely adopted in previous studies on North Sea MHWs, which highlight pronounced contrasts between winter and summer mechanisms (Chen & Staneva, 2024; Mohamed et al., 2023). We will clarify this in the revision.

Results

For me, the Results section is currently difficult to follow, not because the figures are unclear, but because the text does not clearly describe the results shown in the figures. In many paragraphs, the text moves directly to interpretation and discussion without first explaining what is actually being observed. As a result, the reader must go back and forth between the figures and the text to understand what is being claimed.

1. I strongly recommend rewriting the Results section to be more descriptive: each figure should be clearly explained first (what pattern is shown, what changes occur, what differences appear), and only after that should the interpretation be introduced. This would make the manuscript much easier to read.

Response: We thank the reviewer for this constructive assessment. We agree that the current Results section places too much emphasis on interpretation and does not sufficiently describe the observed patterns shown in the figures.

In the revised manuscript, we will rewrite the Results section to provide a more readable structure. For each figure, we will first describe the key observed features (e.g., spatial patterns, temporal variability, and contrasts between regions or periods), and then physical interpretation and discussion. We believe that this reorganization will make the Results section more comprehensible and logically structured, while preserving the scientific content of the analysis.

2. Additionally, in lines 355-361, the manuscript separates the analysis into periods before and after 2013, but it is not clear why 2013 was chosen as a breakpoint. Where is this significant in the results? What evidence supports this split? This section needs more explanation.

Response: We thank the reviewer for requesting clarification on the rationale for choosing 2013 as a breakpoint. We would like to clarify that this choice is not arbitrary but is supported by both our results and independent evidence from existing literature.

First, our moving-window correlation analysis (Fig. R1) reveals a clear change in the relationship between summer MHWCI in Cluster 2 and the IPO around 2013, indicating a shift in the teleconnection structure at that time. We will add this figure to the supplementary of revised manuscript.

Second, previous studies have documented an abrupt cooling in the subpolar North Atlantic during 2013-2014, often referred to as the development of the "cold anomaly" or "cold blob," which coincides with a weakening of the AMV signal during the early 2010s (Frajka-Williams et al., 2017; Josey & Sinha, 2022; Moat et al., 2020).

In the revised manuscript, we will clarify this by explicitly linking the period separation to the moving-window correlation results and by citing relevant studies documenting the North Atlantic cooling and the contemporaneous weakening of the AMV. This additional explanation will make the physical motivation for the 2013 breakpoint clearer and better supported.

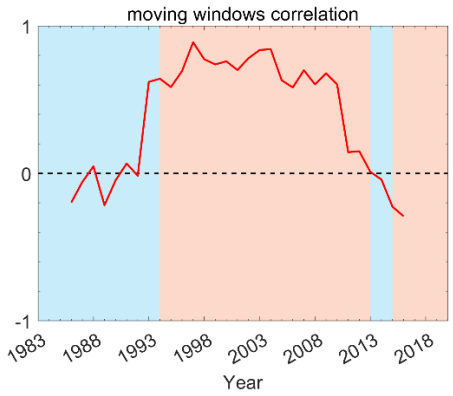

Figure R1. Sliding-window (8-year) correlation between domain-averaged MHWCI for Cluster 2 during summer and Interdecadal Pacific Oscillation (IPO) index.

Minor Comments

L26–27: The sentence is long and somewhat difficult to understand; consider splitting it for clarity.

Response: This sentence will be split to shorter sentences to improve clarity.

L106–112: Please clarify the detrending approach and its spatial application.

Response: We will clarify the detrending approach and its spatial application in the revised Methods. Specifically, detrending is performed by removing a linear trend estimated from the global-mean SST time series over 1982-2021. Monthly global-mean SST is first calculated and linearly interpolated to daily resolution, and a linear regression is then applied to estimate the long-term warming trend. This single global trend is then subtracted uniformly from the full SST field, rather than applying grid-point-wise detrending.

This approach removes the externally forced warming signal while preserving the spatial structure and internal variability of SST anomalies, thereby minimizing the influence of long-term trends on marine heatwave detection, clustering, and climate-mode relationships. These points will be clarified in the Methods section.

L118–124: Seasonal definitions should be explicitly stated.

Response: The seasonal definitions are explicitly stated in the Methods section (Lines 128-130), where seasons are defined as DJF, MAM, JJA, and SON, with DJF treated as a cross-year season.

L194: The sentence structure is heavy; consider rephrasing.

Response: We will rephrase this sentence to improve clarity and readability.

Reference used in the response

Chen, W., & Staneva, J. (2024). Characteristics and trends of marine heatwaves in the northwest European Shelf and the impacts on density stratification. *8th edition of the Copernicus Ocean State Report (OSR8)*, *4-osr8*, 7. https://doi.org/10.5194/sp-4-osr8-7-2024

Frajka-Williams, E., Beaulieu, C., & Duchez, A. (2017). Emerging negative Atlantic Multidecadal Oscillation index in spite of warm subtropics. *Scientific Reports*, *7*(1), 11224. https://doi.org/10.1038/s41598-017-11046-x

Josey, S. A., & Sinha, B. (2022). Subpolar Atlantic Ocean mixed layer heat content variability is increasingly driven by an active ocean. *Communications Earth & Environment*, *3*(1), 111. https://doi.org/10.1038/s43247-022-00433-6

Moat, B. I., Smeed, D. A., Frajka-Williams, E., Desbruyères, D. G., Beaulieu, C., Johns, W. E., Rayner, D., Sanchez-Franks, A., Baringer, M. O., Volkov, D., Jackson, L. C., & Bryden, H. L. (2020). Pending recovery in the strength of the meridional overturning circulation at 26° N. *Ocean Sci.*, *16*(4), 863-874. https://doi.org/10.5194/os-16-863-2020

Mohamed, B., Barth, A., & Alvera-Azcárate, A. (2023). Extreme marine heatwaves and cold-spells events in the Southern North Sea: classifications, patterns, and trends. *Frontiers in Marine Science*, *10*, Article 1258117. https://doi.org/10.3389/fmars.2023.1258117